

# *Fusion Space Propulsion Using Field-Reversed Configurations*



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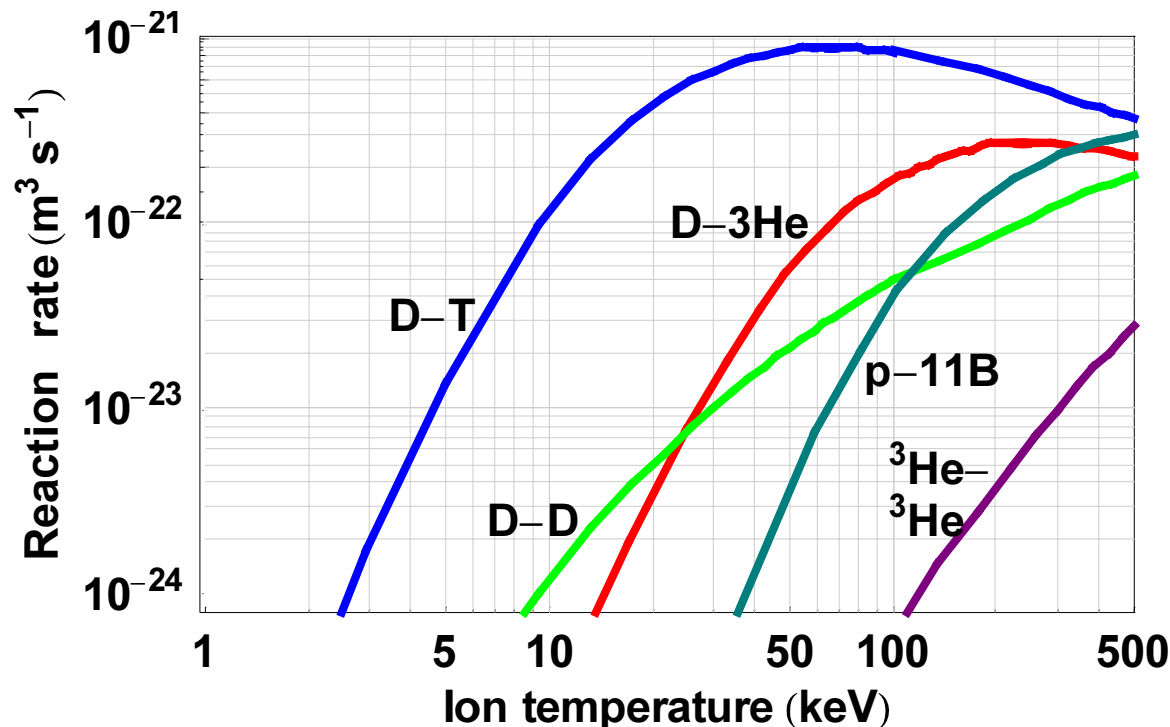
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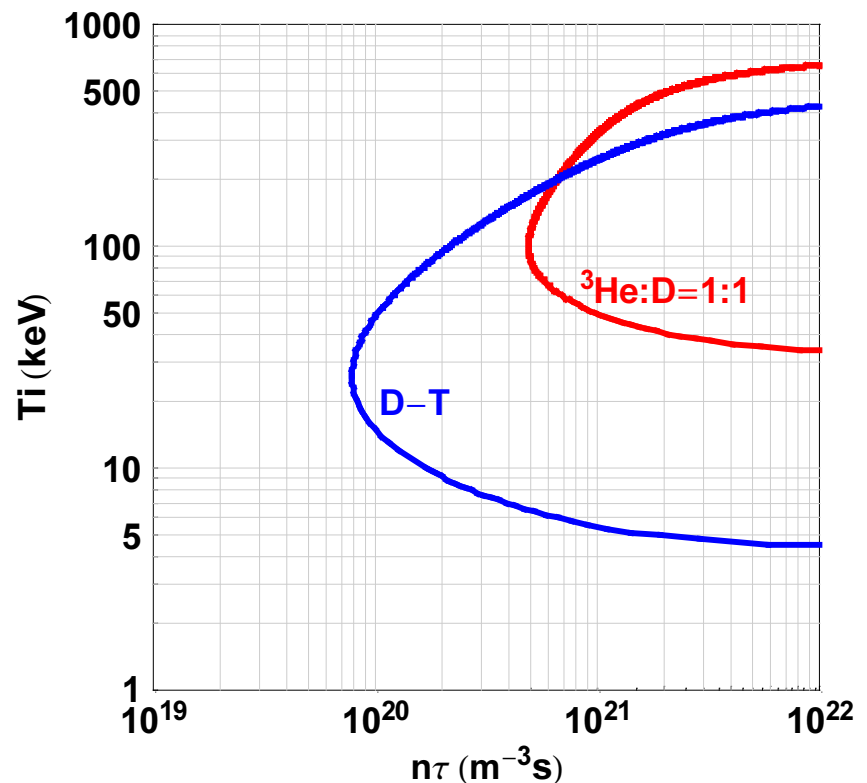
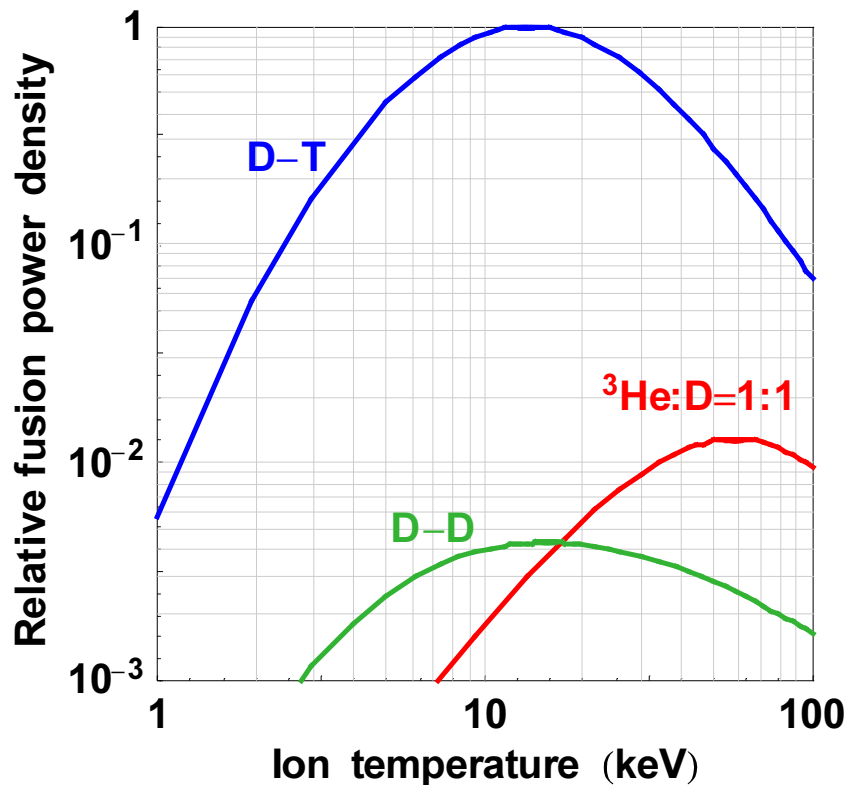
# Key Fusion Fuel Cycles for Space Applications





# Physics Viewpoint: D-<sup>3</sup>He Fuel Requires High $\beta$ , $n\tau$ , and T

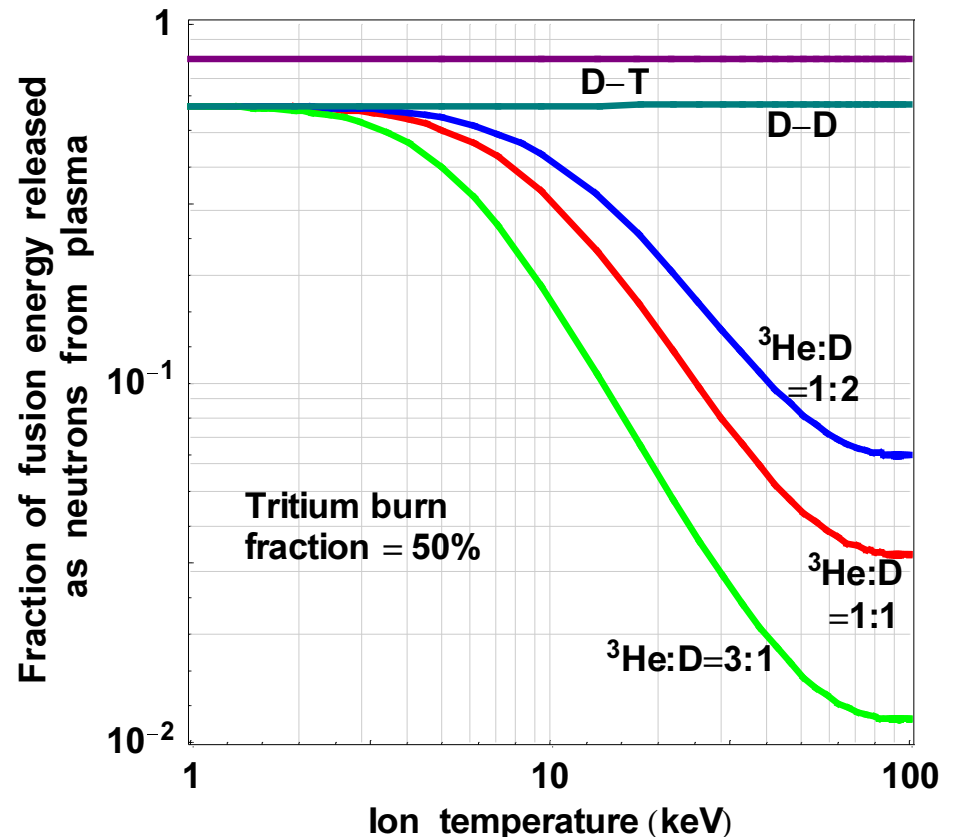
- Power density in the plasma must be increased by utilizing  $\beta^2 B^4$  scaling.
- T and  $n\tau_E$  must each be  $\sim 4$  to 5 times higher for D-<sup>3</sup>He compared to D-T.





# Engineering Viewpoint: D-<sup>3</sup>He Fuel and High $\beta$ Relax Constraints

- Many configurations can increase fusion core B fields, gaining power density due to the  $\beta^2 B^4$  scaling.
- Reduced neutron flux allows
  - Smaller radiation shields
  - Smaller magnets
- Increased charged-particle flux allows direct energy conversion to thrust or electricity





# Sufficient Terrestrial $^3\text{He}$ Exists for an Engineering R&D Program

## Reasonably Assured Reserves of $\text{He}3$ That Could Be Available in the Year 2000

Source	Cumulative Amount (kg)	Production Rate Post 2000 (kg/y)
<b>TRITIUM DECAY</b>		
•U.S. Weapons	300	15
•CANDU Reactors	10	2
<b>PRIMORDIAL</b>		
•He Storage	29	--
•Natural Gas	187	--
	<b>&gt;500</b>	<b>~17</b>

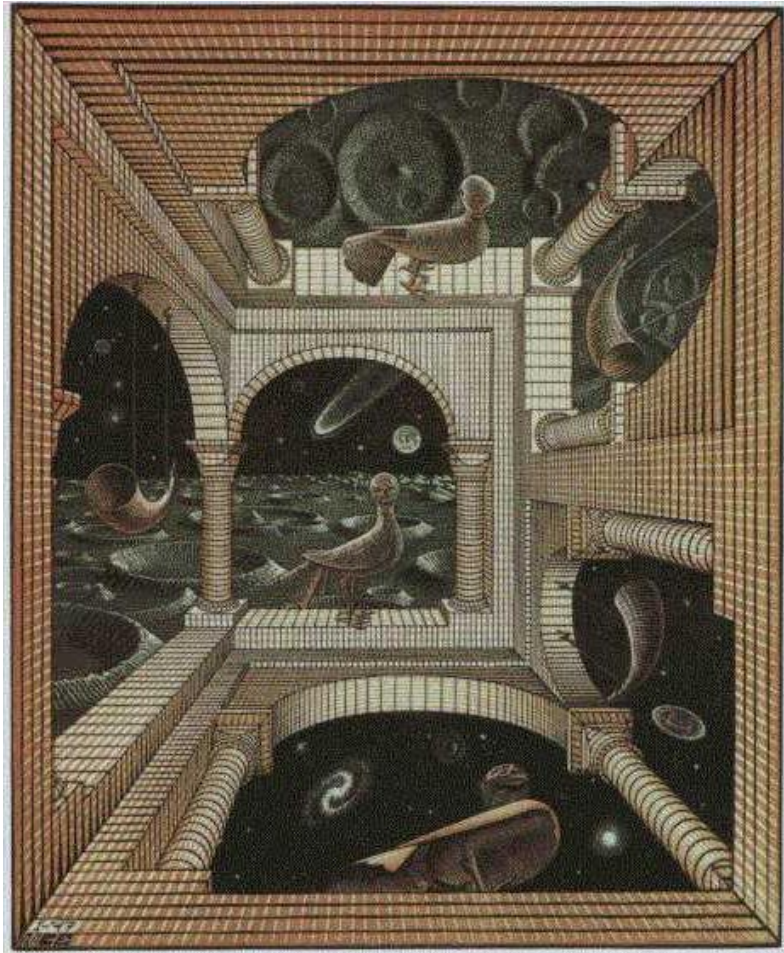
• 500 kg  $^3\text{He}$   $\approx$  10 GW-y fusion energy





# For $^3\text{He}$ Fuel, Think Outside the Box

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- $\sim 500$  kg  $^3\text{He}$  accessible on Earth ( $\sim 10$  GW-a fusion energy for R&D)
- $\sim 10^9$  kg  $^3\text{He}$  on lunar surface for 21st century
- $\sim 10^{23}$  kg  $^3\text{He}$  in gas-giant planets for indefinite future

Escher, Other World, 1947

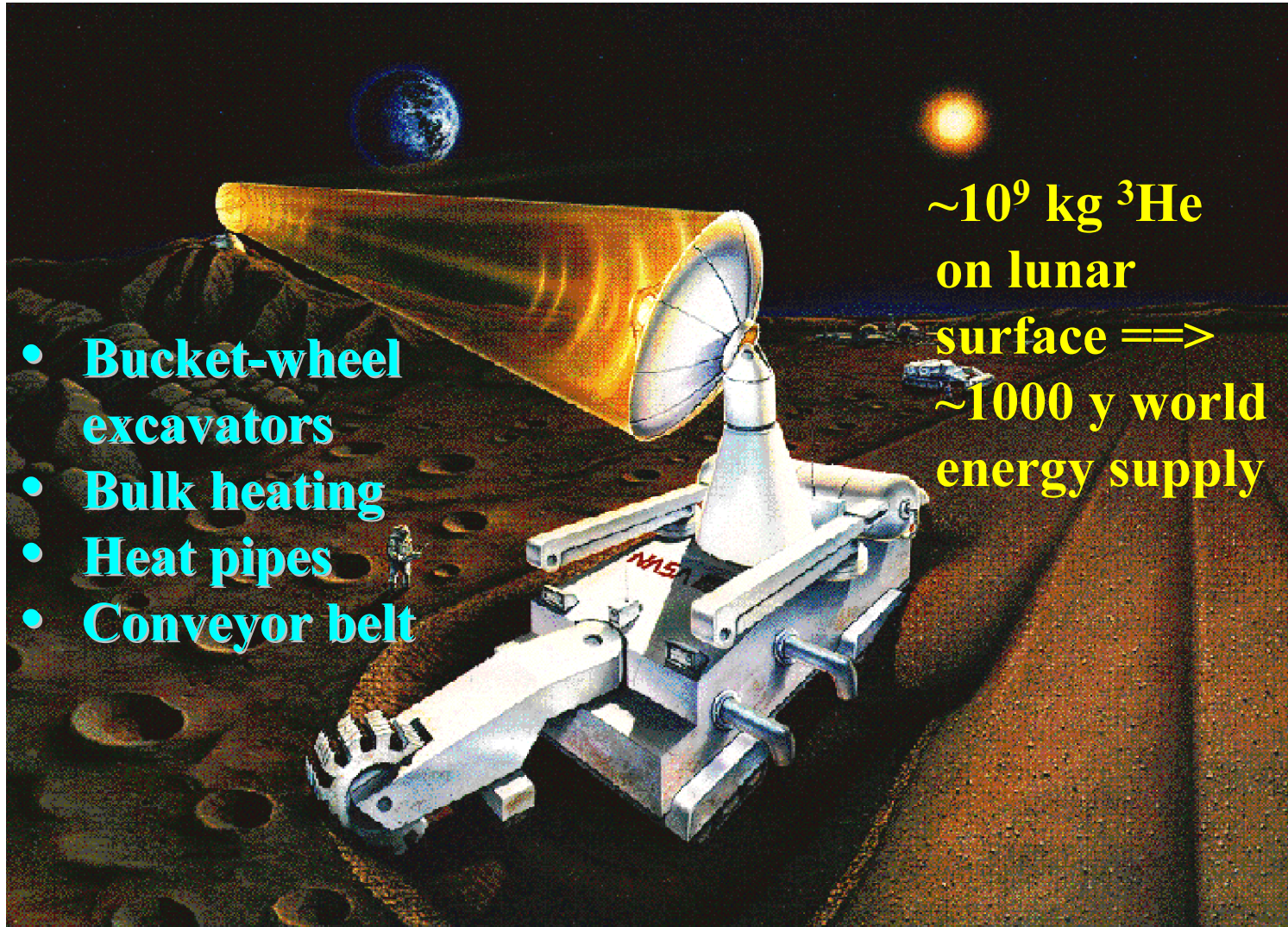




# Well-Developed Terrestrial Technology Gives Access to $\sim 10^9$ kg Lunar $^3\text{He}$

- Bucket-wheel excavators
- Bulk heating
- Heat pipes
- Conveyor belt

$\sim 10^9$  kg  $^3\text{He}$   
on lunar  
surface ==>  
 $\sim 1000$  y world  
energy supply



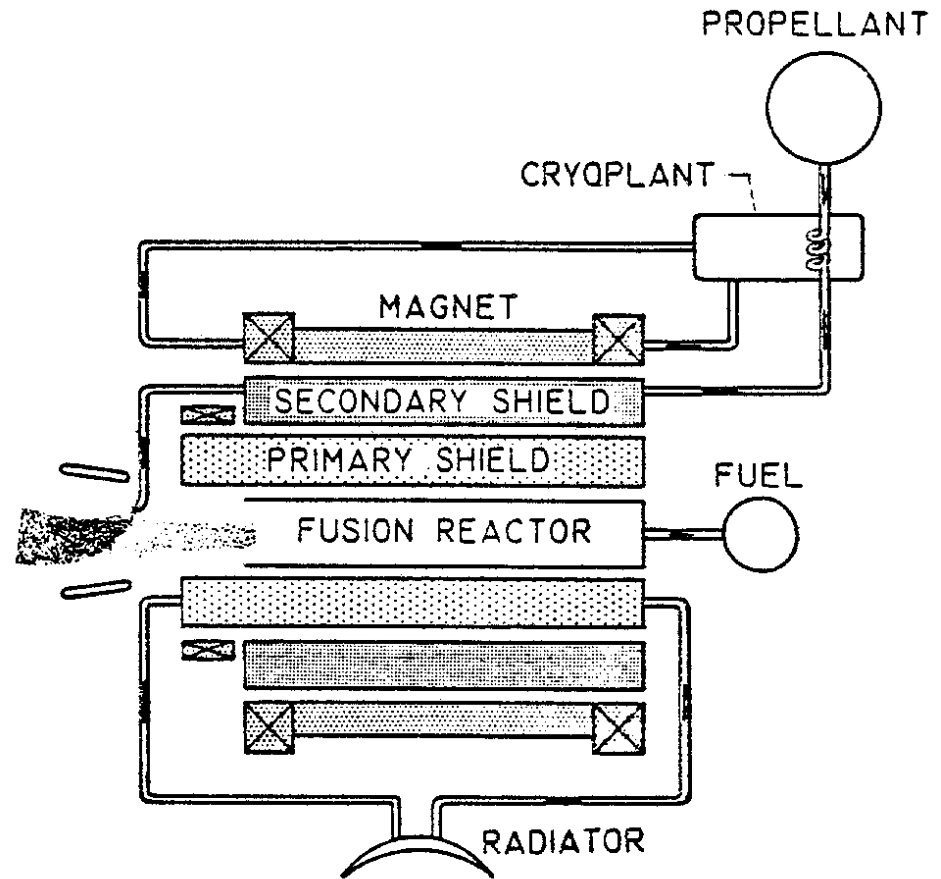


# Earliest D-<sup>3</sup>He Reactor Design Was a Fusion Rocket

G.W. Englert,  
NASA Glenn Research Center  
*New Scientist* (1962)

“If controlled thermonuclear fusion can be used to power spacecraft for interplanetary flight it will give important advantages over chemical or nuclear fission rockets.

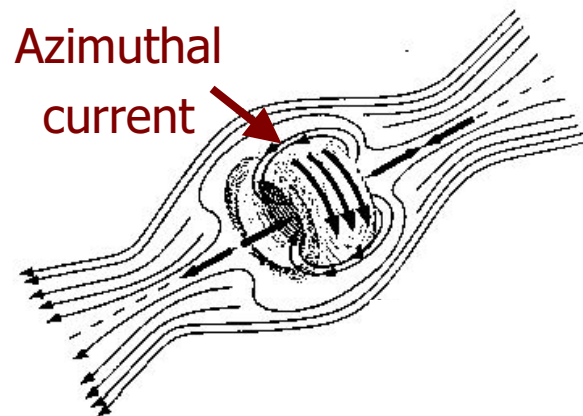
The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement.”



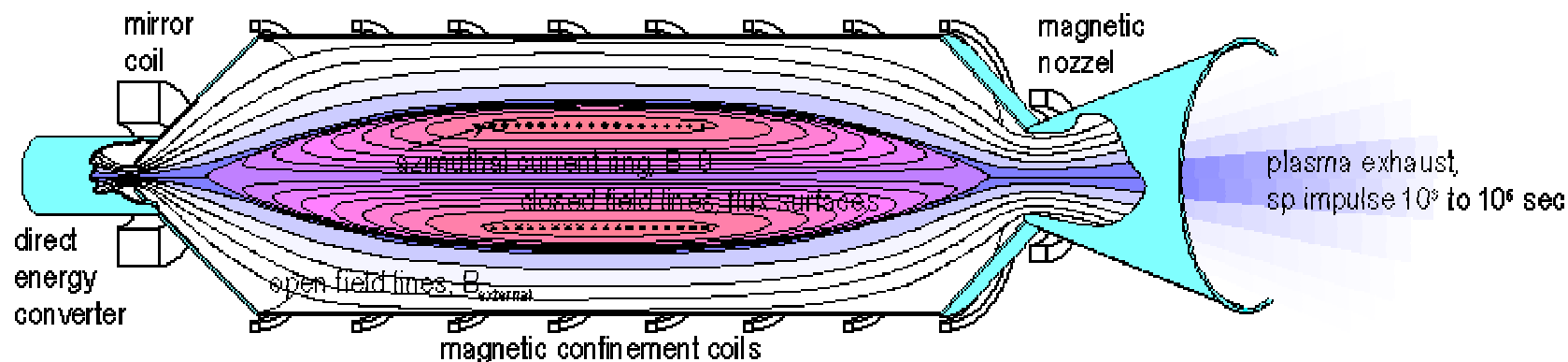




# Field-Reversed Configurations (FRC) Would Be Attractive for Space Applications



- High  $\beta \equiv P_{\text{plasma}}/P_{\text{B-field}}$
- Linear external B field
- Cylindrical geometry
- RMF current drive



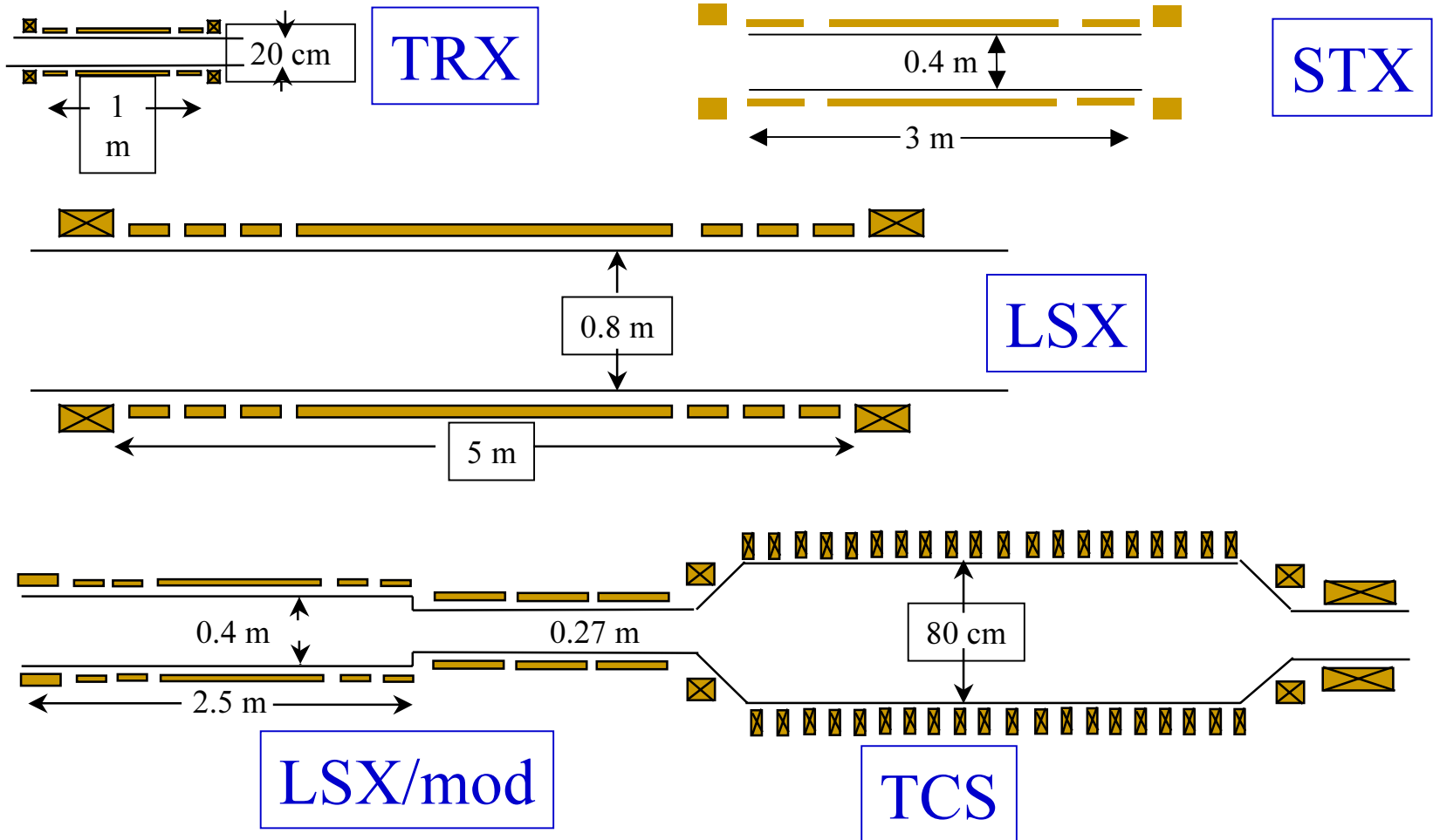
## FRC as Power Source and Ion Engine for High Energy Space Missions

From Univ. of Washington web page for the Star Thrust Experiment (STX):  
[www.aa.washington.edu/AERP/RPPL/STX.html](http://www.aa.washington.edu/AERP/RPPL/STX.html)



# Past & Present

## Univ. of Washington Experimental Facilities

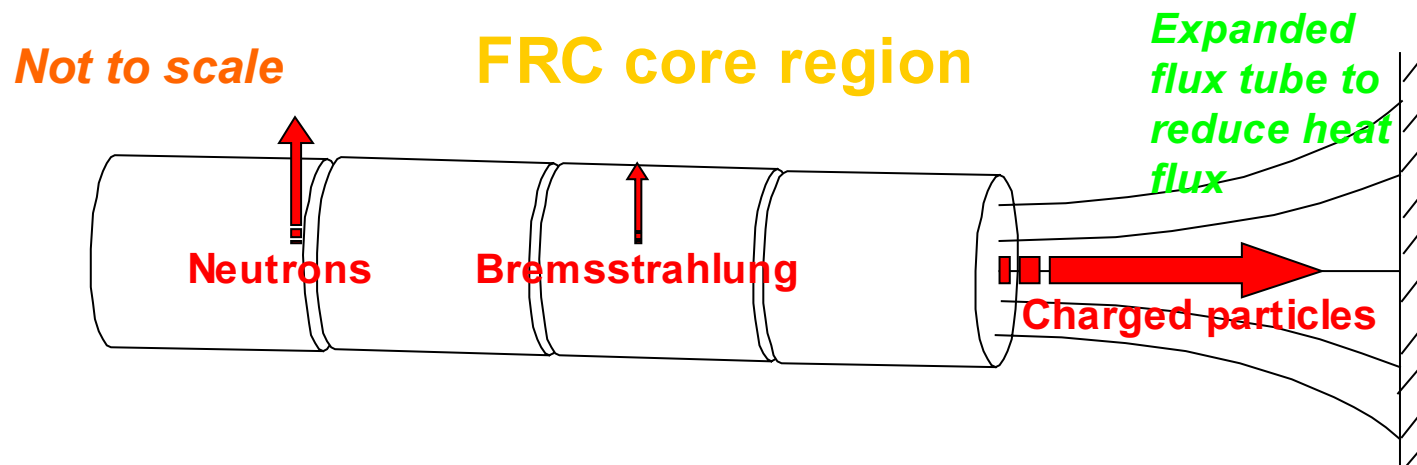


from Alan Hoffman



# FRC Plasma Power Flows Differ Significantly from Tokamak Power Flows

- Power density can be very high due to  $\beta^2 B^4$  scaling, but first-wall heat fluxes would remain manageable.
  - Charged-particle power transports from internal plasmoid to edge region and then out ends of fusion core.
  - Magnetic flux tube would be expanded in end chamber to reduce heat and particle fluxes, so charged-particle transport power only slightly impacts the first wall.







# Linear Geometry Greatly Facilitates Engineering

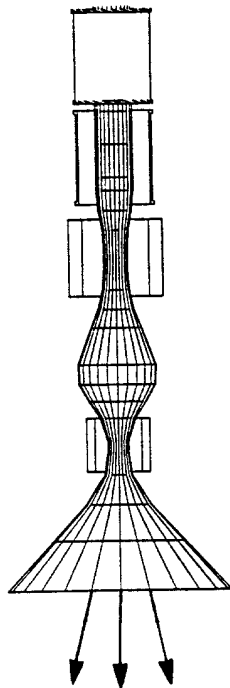
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- Steady-state heat flux is broadly spread and due almost exclusively to bremsstrahlung radiation power.
- Relatively small peaking factor along axis for bremsstrahlung and neutrons.
- Maintenance of single-unit modules containing blanket, shield, and magnet should be relatively easy, improving reliability and availability.
- Considerable flexibility and space exist for placement of pipes, manifolds, etc.
- Direct conversion of transport power to thrust by a magnetic nozzle would increase efficiency.

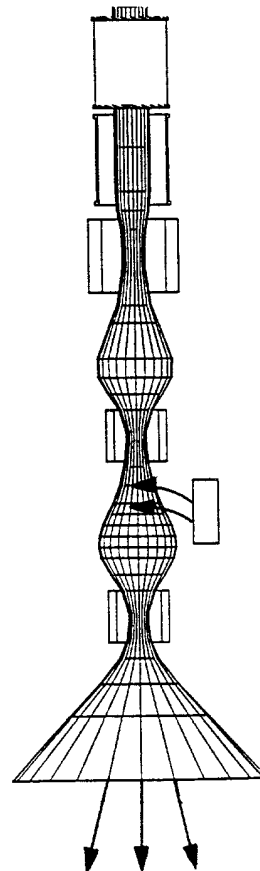


# D-<sup>3</sup>He Fusion Propulsion Could Provide Flexible Thrust Modes

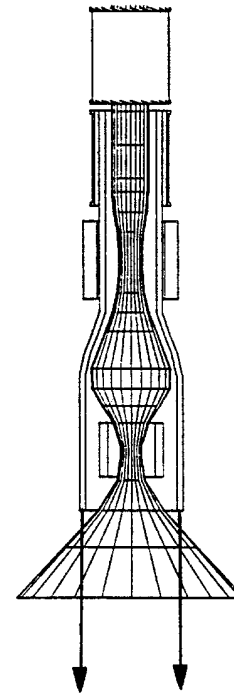
Fuel  
plasma  
exhaust



Mass-  
augmented  
exhaust



Thermal  
exhaust





## Predicted Specific Power of D-<sup>3</sup>He Field-Reversed Configuration Rockets is 5-10 kW/kg

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- Prediction based on J.F. Santarius and B.G. Logan, “Generic Magnetic Fusion Rocket,” *Journal of Propulsion and Power* **14**, 519 (1998).
- Detailed analysis tends to reduce predictions, but the development of high-temperature superconductors will reduce the power-plant mass.
  - Reduced refrigerator mass for magnet coolant.
  - Reduced shielding, because more magnet heating can be tolerated before quenching.
- Work is in progress to apply a more sophisticated analysis to D-<sup>3</sup>He FRC rockets.





# Summary

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- The projected performance of D-<sup>3</sup>He field-reversed configuration (FRC) fusion rockets would allow fast, efficient Solar-System travel.
- The FRC approach constitutes a leading magnetic fusion concept for space applications because of its high power density capability and linear geometry.
- FRC physics development remains the key issue, because the reduced neutron production from D-<sup>3</sup>He compared to D-T fusion eases engineering development.